# Electrical Resistance/Conductivity of CFRP

Subjects: Polymer Science
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This entry provides a comprehensive basis for readers to grasp recent research progresses on electrical behaviors of Carbon fiber reinforced polymer (CFRP), which plays an important role in many fields, especially in aviation and civil industries. The electrical conductivity of CFRP is critical for its electrical behaviors, such as its lightning strike vulnerability, electromagnetic shielding ability, and potential uses for self-sensing. In addition, the electrical conductivity is related to the mechanical integrity. Therefore, electrical properties can be measured as an indication in the detection of delamination and other defects in CFRP.

Keywords: electrical resistance ; conductivity ; carbon fiber reinforced polymer ; anisotropy

## 1. Introduction

Carbon fiber reinforced polymer (CFRP) is a composite material composed of a polymer resin and carbon fibers. CFRP shows an enormous potential in many fields, such as sports and aircraft industry. Particularly, CFRP is widely applied in automotive and aerospace because of its great potential strength, lightweight, non-corrosion and excellent fatigue resistance [1][2].

In the automobile industry, CFRPs account for 17% of auto weight and the application of CFRPs can reduce auto weight by 30%. For aircrafts, CFRPs account for 50% of the total weight of structural elements and the application of CFRPs can reduce the weight of structural element by 20%. CFRP is applied in primary load-bearing structures, such as wing planks, fuselages, sandwich panel skins [3]. Boeing 7E7 containing about 50% CFRPs can reduce 20% of fuel consumption compared to airliners of the same size [4]. Especially, the wings and fuselage of Boeing 787 Dreamliner was made of CFRP [5]. In the future, the weight proportion of CFRPs in aircrafts will exceed 50% [6] and the application of CFRPs will contribute substantially to the reduction of CO2 emission over the total life cycle of aircrafts [7].

However, the application potential of CFRP is generally reduced by high safety factors. During their service life, due to impacts and fatigue loads on CFRPs, local damages such as delamination may be formed. However, the failure prediction is not reliable so far. New problems in these structures made of composite materials remain to be solved [8]. Besides, composites such as CFRP are complex materials exhibiting distinct anisotropic properties [9]. The research focuses on the electrical conductivity of CFRPs, which shows anisotropy and significantly affects the application performance of CFRPs.

## 2. Structure of CFRP and its electrical conductivity

### *2.1. Structure of CFRP*

A carbon fiber reinforced composite is composed of matrix, fiber, and an interphase region [8]. In CFRP, carbon fibers are embedded in a resin matrix. Parallel carbon fibers (conductor) act as the reinforcement material, whereas the polymer resin acts as the matrix [10]. In a CFRP composite, the thickness of a single layer is 0.05 to 0.2 mm and a lamina with fibers in only one direction is called a unidirectional lamina. In order to obtain engineering components, some layers are stacked to form a laminate composed of several plies with different orientations according to the required thickness [11].

### *2.2. Conductivity of CFRP and its characteristics*

In particular, CFRP exhibits poor electrical conductivity and some other unsatisfactory inherent characteristics. Although carbon fibers are good conductors and epoxy resins show excellent properties for wide applications, the electrical insulation behavior restricts their applications in many industries. The electrical conductivity of CFRP can be enhanced by adding conductive fibers [12][13]. This fiber directionality determines the electrical anisotropy in CFRP. The electrical conductivity is much higher in the fiber direction and lower in the direction perpendicular to fiber direction [14]. If the carbon fibers were perfectly straight and did not contact adjacent fibers, CFRP would be highly insulating in the non-fiber direction. Actually, the electrical conductivity of CFRPs in the non-fiber direction is not zero since the ideal conditions cannot be met. Carbon fiber itself is not a straight fiber but a wavy fiber. Due to inter-fiber contact points, the current may flow from one fiber to another [15]. The electric conductance shows similar characteristics in the thickness direction. The inter-lamina makes the electric conductance of the out-of-plane direction much smaller than that of 90° direction. Since the electric conductance of 90° and out-of-plane is related to fiber contacts, the total electrical impedance of a piece of CFRP composites depends on the impedance of all the fibers [16].

As CFRPs are not as conductive as metals and they are anisotropic, it is necessary to understand the electrical conductivity of CFRPs for the purposes of accurately predicting some electrical properties [17][18][19][20][21]. However, the properties are unknown and should be measured in advance[18][22][23][24].

# 3. Relationship between conductivity and other characteristics of CFRP

## *3.1. Self-sensing and conductivity*

The self-sensing ability is important in aircrafts and other industrial applications since it can improve the structural performances. The sensing can be realized through measuring electrical resistance/impedance [25][26]. Strain, temperature and damage can be obtained by monitoring electrical conductivity without embedded sensors [27][28]. The resistivity in the fiber direction could indicate the fiber breakage damage, whereas the resistivity in the through-thickness direction could indicate the delamination damage [27]. The resistivity in both directions could indicate the longitudinal strain since the strain caused the degree of fiber alignment to increase, thereby decreasing the longitudinal resistivity and increasing that in the through-thickness direction[29]. The self-sensing technique is a valuable non-destructive detection method and has been extensively explored [30]. The electrical conductivity of CFRPs has been explored for different applications involving carbon fibers [31][32]. Kupke et al. investigated mechanical damages during fatigue tests by measuring the electrical resistance in specimens [33].

## *3.2. Conductivity and lightning strike*

### 3.2.1. Why is CFRP vulnerable to lightning strike?

CFRPs have high in-plane electrical conductivity but low through-thickness electrical conductivity and can be more easily destroyed by lightning strikes [34][35]. In traditional aircrafts, lightning may flow along the aluminum skin without serious damage. However, composite structures cannot conduct away the large electrical current from a lightning strike and lightning may pass through the aircraft structure, vaporize cables, weld hinges on aircraft surfaces, explode fuel vapors, and generate serious consequences. Damages may lead to the catastrophic accidents of CFRP structures [36][37][38]. Electromagnetic interference may affect the functions of electronic and electrical systems [39].

In previous studies, Feraboli P explored lightning strike damages on carbon/epoxy specimens under different currents and found that electrical conductivity was a key parameter for developing effective lightning strike protections (LSP) [40][41]. Hence, it is necessary to further explore the relationship between lightning strike damage mechanisms and electrical conductivity. The effect of a lightning strike can be reduced as possible by diverting electrical currents or designing the CFRP components [40][42]. These lightning protection measures are also applicable to other vehicles.

Todoroki et al. analyzed the lightning strike behavior in CFRP materials through the impulse current testing [43]. The inhomogeneous and anisotropic property determines the damage types such as fiber failure, delamination or decomposing of polymer matrix. Lately, in order to explain the failure mechanism by means of numerical simulation and experimental testing, the researchers performed a thermal-electrical analysis of CFRP laminates suffered from the artificial lightning striking [44]. The conductivity along the thickness direction was in the linear relationship with temperature. The delamination zones and damage depths obtained from numerical analysis were consistent with the thermal damage area observed from experimental results.

Ogasawara et al. explored quasi-isotropic laminated CFRPs through simulation and experiments and analyzed the lightning strike damage behavior of CFRP structures. Under the peak current of 40 kA, with finite element method (FEM), the damage condition was investigated through thermal and electrical analysis and experimental results were consistent with numerical results [43].

### 3.2.2. How to avoid lightning strike for CFRP?

For the purpose of minimizing lightning strike damage, several solutions have been developed. From the perspective of electrical conductivity, LSP solutions have been adopted in novel aircrafts, including Airbus A350 and Boeing 787. The solutions can largely decrease the lightning strike damage in experimental studies [36][45].

3.2.2.1 Traditional methods

Traditionally, lightning protection of composite aircrafts is based on methods such as incorporating a conductive metallic mesh [36][46]. As a continuously conductive outer layer, the mesh can dissipate indirect or direct electromagnetic interference effects. The similar problems exist in composite structures of other components, such as composite wind turbines and composite masts. More electrically conductive composite structures should be adopted in order to reduce or avoid lightning strike protection materials in aircrafts. Although the efficiency of this method has been verified, the metallic mesh also increases the weight and offsets the advantages provided by the high strength and stiffness of CFRP [47].

3.2.2.2. Novel methods

Several techniques were developed to increase the conductivity of epoxy. Carbon black was generally used as the reinforcement to increase the conductivity of epoxy. CNT reinforcement has been recently applied for this purpose since CNT has excellent mechanical properties and high electrical and thermal conductivities [48].

### *3.3. Conductivity and electromagnetic shielding*

Electromagnetic interference (EMI) shielding is also widely concerned in communication and electronic industries [49][50]. EMI refers to the ability to block electromagnetic radiation [51]. EMI refers to the ability to block electromagnetic radiation [51]. CFRP composites, used in aeronautic industry, have a good shielding and absorbing effectiveness while presenting high mechanical and chemical resistance per unit weight [52]. The high electrical conductivity of carbon fibers allows the good electromagnetic shielding effect since the electric field lines are attracted to conductive fibers and result in surface electric currents[53][54][55]. Therefore, it is necessary to explore the structure and function of carbon fiber-based composites[56]. The orientation and distribution of carbon fibers largely influences the electrical conductivity and shielding effectiveness of the composites. The exposed clearance and the destroyed conductive network mainly led to the decrease in the shielding effectiveness[57].

Two common approaches are generally used to achieve EMI shielding of CFRP for plastics products. One is coating with the conductive metal, the other is blending with conductive fibers or particles [58]. The addition of metal powders into CFRP composites was a cost-effective method for improving shielding effectiveness [59].

The incorporation of conductive fillers in the polymer matrix can improve the electrical conductivity of plastics and solve the EMI problem. In addition, metal-coated carbon fibers also endow polymer composites with high modulus, light weight, and high strength [60][61][62].

Another method [63][64] mentioned that the polymer matrix in the composites was typically electrically insulating, so it could not provide shielding. However, electrically conducting fillers endow the composites with the shielding ability. Both discontinuous and continuous fillers are used for this purpose [65].

## 4. CFRP conductivity measurements and techniques for non-destructive testing applications

In most cases, electrical conductivity is an important parameter providing useful information for CFRP quality assessment, non-destructive testing and performance improvement. In the following sections, different techniques for CFRP conductivity measurements are described and classified according to different applications.

### *4.1. Conductivity for non-destructive testing*

In spite of the above advantages, CFRPs are not used at their full potential in critical load-bearing structures because it is difficult to track the initiation and propagation of damage. As a consequence, CFRPs are not designed optimally, but they are designed with a high safety factor. Therefore, long-term critical structural applications, require low-cost and reliable techniques to detect possible degradation [66][67].

Defects in all composite structures may result in a loss of mechanical properties and tend to increase with structural complexity. Defects arise in the production process, when they are expected to be repaired if detected, and during service [3].

Delamination is one of the common failure modes. In all the types of the damages in laminated structures of CFRP products, the proportion of delamination damage reaches 60% due to the low through-thickness strength. Therefore, the delamination characteristics largely determine the safety of CFRP products. A delamination is a crack in the resin component between plies of different fiber orientations. Delamination seriously affects the performance of CFRP products and may cause serious failures because it is difficult to be visually detected[68]. Small areas of delamination can cut off more than 50% of the compression strength. Delamination decreases the stability of the load-bearing fibers and may lead to a localized buckling-type of failure mode even under low loads[69][70][71]. Previous studies on delamination focuses on delamination detection through electrical conductivity and the way to prevent delamination by improving CFRP conductive performance.

### 4.2. Delamination measurements based on electrical conductivity

The basic principle of delamination test is that cracks and damages are obstacles in an electrical current path. Therefore, such cracks and damages can increase the electrical resistance. The size, shape, and orientation of such damages/cracks determine the resistance change, which thus can be used as a detection indicator of delamination[66].

Due to compound material structures, many destructive methods and non-destructive techniques have been developed for CFRPs [70], including eddy current testing (ECT) [71][72], inductive thermography [73], and electrical resistivity change methods[74].

#### 4.2.1. Eddy current testing

Eddy current testing (ECT) can be used to detect CFRPs. Based on electromagnetic principles, ECT is more suitable for electrical conductive materials such as CFRPs[75].

In ECT, a current-carrying coil is positioned just above the component surface to induce an electrical field in the composite. Flaws in the material can interrupt the current field and change the impedance in the coil. The defect severity can be explored based on the changes in amplitude and phase angle of electrical signals[76][77].

Theoretically, eddy current testing is not sensitive to delamination because eddy currents are flowing in the direction parallel to laminates and changed slightly by the delamination. It is concluded that eddy current methods are much more sensitive to broken fibers than delamination[78]. The comparison between ECT and ultrasonic inspection confirmed that the ultrasonic method could precisely detect delamination defects, but the detection results were not consistent with ECT results. However, some satisfactory results have been obtained. ECT with the high reproducibility and good signal-to-noise ratio is a low-cost technique for detecting delamination in CFRPs[79].

Three techniques mentioned above can be used to analyze the delamination in CFRPs[80]. However, the extent of delamination as viewed in the C-scan image and SAM image was different from the results achieved by eddy current inspection. Though it was not possible to distinguish the two types of defects due to the low resolution, ECT detected both delamination and interlaminar cracks. Experimental results [79] clearly showed that eddy currents could detect delamination growth. Therefore, ECT is a potential method for monitoring defects in CFRPs.

However, if the sensor used is not optimized according to the frequency requirement for detecting deeper defects, when delamination occurs in deeper zones, chaotic conductivity arrangements increase the detection difficulty of delamination [81]. Therefore, these layers or the real volume extension of the delamination is not complete. Larger sensors with the lower resolution but deeper penetration depths at higher frequencies should be adopted in ECT. To sum up, because of the low electrical conductivity of carbon fibers, the excitation frequency range of the inductors used in ECT for composites is 100 kHz~100 MHz [82].

#### 4.2.2. Electrical resistance change method

Most of the reported studies on CFRP testing focused on the electrical resistance change method (ERCM) for monitoring the bulk resistance of the CFRPs[83][84]. The relationships between the recorded electrical resistance change and other conditions (loading conditions and/or mechanical degradation of materials) were obtained. Experimental findings were verified with finite element (FE) models. Electrical methods, such as ERCM, can sense the evolution and development of damages in CFRPs[84][85][86].

ERCM had been used to detect the internal damage of CFRP laminates. The through-thickness resistance is responsive to delamination. Since CFRP was adopted as sensors for damage detection in the method, ERCM did not decrease fatigue strength or static strength. ERCM is suitable to existing structures. ERCM does not increase the structural weight and shows the good monitoring performance in stiffness reduction caused by fatigue loads. The damage accumulation process can be observed[86][87][88][89][90].

Zappalorto M studied the electrical response of a conductive laminate with a delamination, experimentally confirmed the relationship between orthotropic electric conductance and fiber volume fraction, and explored the effects of measured orthotropic electric conductance on delamination monitoring through FEM analyses[16]. Selvakumaran L developed an electrical meso-model based on the consideration of transverse cracks with local delamination for in-plane loading and then increased the consideration of the out-of-plane loading[66]. The model indicated that the through-thickness and transverse conductivities of the ply could be changed by the transverse cracking with local delamination. The model capability and accuracy had been proved[66]. The fiber volume fraction has significant effects on the through-thickness and transverse electric conductance and the through-thickness electric conductance significantly affects the delamination detection results with ERCM [87]. The influences of transverse cracks along with delamination were explored by the response surface method [88][89][90]. The method successfully identified the delamination size and location. The effects of matrix cracking on electric resistance changes between electrodes were explored by FEM analyses [88]. The data set of electric resistance changes can be obtained for calculating response surfaces through the simple calculation with a straight delamination crack model. The data normalization method can significantly improve the estimation performance[86]. Half of the applied electric current flowed in the surface layer along the fiber direction, whereas the other half tended to flow in the bottom surface layer along the fiber direction [90]. The difference caused the electric current flow along the thickness direction as well as a large electrical resistance change in front of a delamination crack. The same research group monitored the location and dimension of a delamination crack in the specimen through multiple electrodes mounted on the single surface[91]. The relationship between delamination locations/dimensions and measured electrical resistances were experimentally explored by response surface method and the least square errors method.

The ERCM involves the application of two or four electrodes for sending current and different numbers of electrodes for measuring voltage[89][92]. The differences between two-electrode ERCM and four-electrode ERCM are listed as follows[93][94]:

1) Four electrodes: In the four-probe technique for piezoresistance analysis of CFRP composites, both the inner measurement electrodes and outer current introduction electrodes are mounted on the external laminate surface and subjected to the mechanical strain. Compared to two-electrode technique, four-electrode technique is suggested for monitoring the changes in resistance. The four-electrode technique can avoid the effect of potential contact resistance changes at the inner electrodes under the influence of mechanical strain on the contact.

2) Two electrodes: Why the two-probe technique other than the four-probe technique was adopted in some experiments? Firstly, it can avoid the effect of mechanical strain on the inner probes. Secondly, it can make sure that the measured potential difference reflects the effects of all the carbon fibers in the entire sample cross section, other than that of the fibers adjacent to the laminate surface. Wang and Chung indicated that the two-probe technique might lead to the misunderstanding because the method included the electric resistance change of electrodes.

The change in electric potential caused by delamination was calculated with the equivalent electric conductance and the method had been proved with the finite different method (FDM) [90]. ERCM is proved to be an effective method to detect the CFRP delamination. However, ERCM requires a huge amount of hardware circuits to supply an alternating current (AC) between all adjacent electrodes. The measurement precision is strongly affected by the contact state between copper electrodes and specimens. Most of these studies in this field were experimental studies. The mechanisms of damage to the bulk resistivity change were not theoretically explored [83].

#### 4.2.3. Electrical potential change method

In addition to ERCM, the electrical potential change method (EPCM) was also employed to sense CFRP delamination. EPCM measures the change of electric potential difference based on the changing electric current at the two electrodes installed at two opposite ends of a specimen[95].

In ERCM and EPCM, two electrodes are used to send current and different numbers of electrodes are used to measure voltage. The difference between them lies in the potential measurement direction. In ERCM, the applied current line coincides with the electric potential line. In EPCM, the two lines do not coincide with each other[96][97][98]. The one-dimensional (1-D) ERCM is enough for sense the damage distribution. A two-dimensional (2-D) method is required for determining the damage location. In the 2-D ERCM, a large array of contacts are required to cover the surface. According to the ERCM mechanism, each surface requires 3 contacts, which cannot be realized in the two-dimensional resistance method. The 1-D EPCM avoids the disadvantages since it can be applied with only the contacts along specimen edges. The current is applied with one pair of contacts and other contacts are used to measure the voltage[99].

Early in the 1990s, Todoroki et al. in Tokyo Institute of Technology explored EPCM and largely contributed to the development of non-destructive testing of CFRP [100]. Todoroki combined the response surface method with EPCM to determine a delamination in the laminate [101][102]. However, extensive experimental data are required in these models for calibration. The calibration is performed for a given experimental condition. Todoroki et al. also employed a normalization method to improve the delamination detection performance. The improved method showed the better detection performance for the delamination near specimen edges, but the low performance for the delamination in the middle of the specimen[103]. A new two-stage estimation method was used to solve the problem and showed the better performance than FEM analysis [104].

### 4.3. Methods to avoid delamination

The electrical conductivity of CFRPs was generally increased in order to prevent delamination cracking [105]. In addition, resin-rich layers with elastomer particles were also used to toughen laminated CFRP [45]. However, the highly toughened CFRP showed the lower electrical conductivity than common laminated CFRP [44]. The electrical conductivity of the former is significantly orthotropic and easily lead to structural damages in case of lightning strike [43].

### 4.4. Measurements for other flaws (Taking fiber waviness as an example)

When CFRPs are molded, defects may be generated in the CFRP. Fiber waviness, a typical defect, refers to fiber deformation and is induced by axial loading of carbon fibers [106]. In thin laminates, out-of-plane motion of carbon fibers is limited, so in-plane waviness may occur [107]. However, under large temperature gradients along the thickness direction, out-of-plane waviness is induced in thick laminates [106][108].

Mizukami and his colleagues [109] proposed a novel probe to detect out-of-plane and in-plane fiber waviness in unidirectional CFRPs and characterized the orientations with an ECT. The novel probe could detect in-plane fiber waviness (amplitude: 1.1 mm; length: 15.9 mm) in a thin unidirectional CFRP specimen at a sufficiently high working frequency. FEM was also used to verify the proposed method. Variations in phase and amplitude of received signals obtained in numerical simulation were well consistent with experimental data. The probe could detect out-of-plane fiber waviness in a thick CFRP specimen. The out-of-plane fiber waviness was determined based on ring-shaped plots in complex plane. K. Mizukami et al. [110] analyzed the obtained signal with extreme values at the edges and waviness vertex and proposed the possibility of precise waviness location identification.

The variation of the electrical resistivity of CFRP specimens could be taken as a damage analogue and the related methods could be used in situ as a non-destructive technique (NDT) for continuously monitoring the working condition of CFRPs [111]. These methods could improve the quality of composite panels and monitor structural health of CFRP components [29].

## 5. Necessity and methods to increase the CFRP conductivity

In recent years, CFRP has been widely applied in many fields, particularly in aircrafts.  Compared to metal materials, CFRPs can significantly decrease the weight of structural parts and have been increasingly widely applied. Epoxy resins with good properties had wide applications, but they showed the undesired electrical insulation and limited the global electrical conductivity of CFRPs [112]. High electrical conductivity is required in aircrafts for lightning protection and EMI shielding[85][113][114]. Carbon black (CB), Carbon nanotubes (CNTs), and other nano-particles, have been used to improve the mechanical performance of composites. Key performances of the systems constructed with CFRPs have been significantly improved by the above products of nanotechnology. New plastic materials, such as polyaniline (PANI), are introduced as an effective method to improve the conductivity of CFRPs[85][115].

### 5.1. CNTs/CB

CNTs could largely enhance the electrical conductivity of polymers and improve the interlaminar fracture toughness of CFRPs[116][117][118]. In particular, the incorporation of CB significantly reduced the epoxy resistancec[119]. CNTs have the better conductivity than CB. CNTs could be filtered by dense CF bundles, so CNTs could not be applied in advanced liquid molding processes.

#### 5.1.1. Carbon nanotubes

CNTs-polymer composites have gained popularity recently over metals[120][121]. After CNTs were first reported by S. Iijimain in 1991[122], they have been extensively explored[123][124][125].

CNTs are new advanced materials, especially in EMI shielding and electronics of aircrafts. CNTs may exist as a fabric-like format and can be integrated into composite materials. CNTs in the coating form can realize the better shielding performance. The tensile strength of CNTs is higher than that of carbon fiber, but CNTs are more flexible. CNTs can improve the EMI shielding effectiveness via absorption and reflection. Adding CNTs significantly improved the absorption, which becomes the main shielding mechanism[126].

#### 5.1.2. Carbon black

CB is the mainstream reinforcing filler applied in rubber compounds. CBs are generally fused into aggregates in CFRPs[51][127]. CB is a semiconductor and closely related to the rubber industry. When it is used as a filler, it can endow the product with conductive/anti-static properties[128].

SE increases with the increase in DC conductivity. The increasing process can be divided into two stages. Firstly, when the DC conductivity increases below the percolation threshold, SE increases slightly. In this stage, a slight change in the content of carbon filler may lead to the dramatic increase in the conductivity, but its effect on the SE remains marginal. Secondly, when the DC conductivity increases above the percolation threshold, a slight change in DC conductivity significantly increases SE. In this stage, even though the conductivity increase is not significant, the shielding properties are highly sensitive to the slight DC conductivity variation[51].

### *5.2. PANI*

Nanoparticles were often used to increase the electric conductivity of CFRPs. The through-thickness conductivity was increased by adding CB and CNTs into CFRP laminates[51][129]. However, this improvement is limited by an electrical percolation threshold. For instance, multi-walled carbon nanotubes (MWCNTs) in CFRPs had an electrical percolation threshold of 2 wt.%.

Polyaniline (PANI) has various applications in electrochromic devices. Insoluble PANI can be doped into an insulating polymer matrix. Yokozeki reported the development of CFRPs based on PANI- to increase electrical properties and found that the obtained CFRPs had the high electrical conductivity along the thickness direction[130]. Based on the conductivity analysis, electromagnetic shielding properties of the developed CFRPs were also explored.

### *5.3. Conductivity improvement with nanotechnology and plastic materials*

Conductive nanocomposites as the matrix could change electrical properties of CFRPs[131][132][133]. In the manufacturing process of nanocomposites with polymers and conductive fillers, some drawbacks are generally generated[134]. Sufficient conductive nanofillers should be added to guarantee high conductivity. However, too much conductive nanofiller also results in the increased viscosity of the nanocomposite mixture, thus making the production process of CFRPs difficult[135]. The agglomeration phenomenon of nanofillers often occurs due to the incomplete mixing, thus decreasing mechanical performances[136][137].

Although the above methods had their own disadvantages, they could enhance the conductive performance significantly. The electrical conductivity of CFRPs was almost 12 orders of magnitude higher than that of pure epoxy resin after adding 0.5 wt% MWCNT[115]. The air-spraying method was investigated in order to enhance thermal and electrical conductivities. Single-walled carbon nanotubes (SWCNTs) with carboxylic acid groups were air-sprayed on the surface of carbon fiber prepreg, which were stacked and processed into carbon fiber laminates[138]. It was discovered that the electrical conductivity was largely improved by SWCNTs, but the thermal conductivity was not ameliorated. The electrical conductivity of CNT/polymer composites was increased to 10-3 S/cm by ~1.0 wt% CNTs. Similarly, after CNTs were grown for only 3 min, the interfacial properties and electrical conductivity of the CFs were increased largely. The in-plane electrical conductivity was improved by more than 170%. The interfacial shear strength of carbon fiber/epoxy composites was increased by ~70%. The electrical conductivity in the through-thickness direction was improved by 44% [139].

Novel multi-functional composites can be developed based on the synergetic effect of different ingredients. In summary, a synergistic enhancement has been obtained in the electrical conductivity of the hybrid CFRP laminate system incorporating CNTs, PANI, and CB [30][48][140][141][142][143].

Ruoff explored the damage behavior caused by the lightning strike of carbon nanotube (CNT) doped CFRPs and found that increasing the content of CNT in the resin significantly decreased the damage region, indicating that the electrical conductivity in the through-thickness direction of the plate determined the lightning strike damage[144].

## 6. Conclusion

CFRPs play a key role in many industries. CFRP composites are expensive, but valuable in many fields. Especially, CFRPs are extensively used in aircrafts. New large aircrafts are designed with composite wing and fuselage structures. Aircraft operators indicated the demand for product upgrades, and aftermarket providers have provided the solutions for improving the performance and efficiency of legacy aircraft by incorporating composites. Electrical behaviors of CFRP composites largely determine their multi-functional applications under electrical effects and have been widely explored.

The electrical conductivity of CFRPs is important for monitoring structural health and protecting aircrafts from lightning strike. Recent studies on the electrical conductivity of CFRPs are mainly focused on the electrical conductivity of single carbon fibers. Due to the anisotropic properties of carbon fibers, the electrical conductivity of CFRPs should be anisotropic as well and cannot be fully obtained via bulk measurements of CFRP composites. Related studies are largely restricted because existing experimental techniques cannot be used to examine the anisotropic features of CFRPs. This is an ongoing work and much yet to be explored.

In the future development of CFRP, more accurate simulation models and theoretical analysis are required to improve the understanding of CFRPs conductive behaviors in different applications. The microstructural study of CFRPs may promote the breakthrough of CFRP development. The CFRPs industry has the promising prospect and new innovative products will be developed.

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